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THE HYPERSONIC ENVIRONMENT--
HEAT TRANSFER IN MULTICOMPONENT GASES

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THE HYPERSONIC ENVIRONMENT --
HEAT TRANSFER IN MULTICOMPONENT GASES[*]

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CONTENTS

ABSTRACT

      The prediction of heat transfer in the high temperature hyper-
sonic flight regime continues to be a challenging problem, particularly
with the increasing need to understand the phenomena from a microscopic
viewpoint. In this review paper, the general hypersonic heat transfer
problem, for an arbitrary planetary atmosphere, is introduced by clas-
sifying the various regimes of interest. Recent developments in each
of these regimes, ranging through the free molecule, near free molecule,
low Reynolds number and high Reynolds number regimes are considered.

      Some of the latest techniques for predicting aerodynamic and
radiative heat transfer are discussed, and uncertainties are pointed out.
Throughout the paper, special emphasis has been placed on a discussion
of thermophysical phenomena, which points out the need for the intro-
duction of classical, statistical and quantum mechanical approaches to
the development of realistic models for the hypersonic interaction problem.

INTRODUCTION

In this paper, a discussion will be presented of some of the techniques and results which may be utilized in analyzing the thermophysical and aerothermochemical nature of the hypersonic flight environment, and some of the latest methods will be reviewed for the prediction of the magnitude of the aerodynamic and radiative heat transfer during hypersonic flight in a planetary atmosphere.

For a given hypersonic vehicle, which may have a sub-orbital, orbital or super-orbital mission, the severity of the heat transfer problem is intimately related to the precise flight corridor or trajectory. That is, one must first have a knowledge of the vehicle flight speed and ambient environmental conditions as a function of altitude, since together they define the aerothermochemical nature of the vehicle-environment interaction problem, as well as the exposure time. These initial conditions may be readily obtained by analytical or numerical techniques which have been developed[1-6] to solve the equations of motion of the vehicle for a specific model atmosphere,[7] and here we need not restrict our discussion to Earth's atmosphere.[8] However, we will not dwell on the question of uncertainties in the structure and chemical composition of the atmosphere of a given planet. Rather, it is assumed that sounding rockets, satellites, and fly-by or entry planetary probes carrying spectrometers,[9] ion gauges, etc. either have been or will be utilized to establish reasonable

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models for the environmental conditions in the undisturbed atmosphere. Hence, the ensuing discussion will focus on the twin problems of aerodynamic and radiative heat transfer at hypersonic flight speeds.

It should be noted that after the relationships between the hypersonic heat transfer rates and the local environment have been established, at least for lifting entry vehicles, one may return to the trajectory problem and consider the question of the determination of optimum trajectories. That is, by means of a mathematical approach based on the calculus of variations, one can determine a class of flight paths which minimize the severity of the hypersonic thermal problem on a time-integrated basis, for the complete mission. [10, 11]

REGIMES OF HYPERSONIC FLIGHT

The aerodynamicist and physicist have usually found it convenient to characterize different regimes of atmospheric flight in terms of certain dimensionless groups, such as the Mach number, Reynolds number and Knudsen number, [12, 13] simply because theoretical and experimental techniques and correlation formulas have usually been found to be applicable over a certain range of flight conditions and vehicle geometry. However, as many new techniques are developed and greater understanding is achieved, a certain tendency towards generic classification results, [14-19] since one is tempted to establish a clear demarcation for each new sub-class of vehicle environment interaction problems.

Perhaps, there would be no need for additional classification of flight regimes if one could always solve the non-linear Boltzmann equation, regardless of the thermophysical nature of the incident gas flow. However, any kinetic master equation presents a formidable challenge to the theoretician, and complete solutions for hypersonic flow, without the assumption of linearization are yet to be achieved.

For hypersonic flight, it is convenient to define the flow regimes in terms of the molecular phenomena encountered during the development of the flow field as a space vehicle enters a planetary atmosphere, see Fig. 1. This figure shows a relatively simple classification scheme, as well as two typical trajectories for sub-orbital entry into Earth's

atmosphere.

At the highest altitudes, where the mean free path is large compared to a typical vehicle dimension, the Knudsen number, which is defined as the ratio of the mean free path to a reference length, is much larger than unity. Due to the extreme rarefaction of the gas, the reflected gas molecules collide infrequently with the incident particles, and all interactions involving energy transfer therefore tend to occur immediately at the vehicle surface. This is known as the free molecule flow regime.

As the vehicle penetrates the stratified atmosphere more deeply, the density of the ambient gas increases, and the frequency of collisions between incident and reflected molecules increases to such an extent that the velocity of the incident stream is perturbed by the presence of the molecules issuing from the surface of the vehicle. This is known as the near free molecule flow regime.

As the free stream density continues to increase, the extent of the interaction between incident and reflected molecules is more pronounced and the zone of interaction begins to coalesce into a shock wave. This is known as the transition regime, since it delineates the onset of the region in which macroscopic gas phenomena start to dominate over microscopic phenomena in the bulk gas flow.

At still lower altitudes, a fully developed shock wave is present in the flow a finite distance upstream of the vehicle, and the flow between

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the shock wave and the vehicle surface is fully viscous. [15-18] In this

low Reynolds number flow regime, one can distinguish further between

conditions of partial or full merging of the structure of the shock wave

with that of the viscous layer at the vehicle surface. It is noted that the

same low density effects which result in the thickening of the boundary

layer during high altitude flight also promote the broadening of the shock

wave. [18, 20] Thus, although one is accustomed to thinking of a shock

wave as a flow discontinuity, this is not the case during high altitude

flight, where the large mean free paths and the lower inter-molecular

collision frequency produce a much larger space-wise distribution of all

collision dependent phenomena than would be the case at lower altitudes.

At the lowest altitudes, the shock Reynolds number, which is

directly proportional to the free stream density, is sufficiently large so

that the viscous layer separates into two distinct regions in the flow field.

The shock wave thickness decreases and behaves essentially like a dis-

continuity in the flow. The viscous layer thickness decreases and be-

comes a thin boundary layer, which can be treated within the framework

of Prandtl's original assumption concerning the absence of a pressure

gradient normal to the surface. The flow between the shock wave and

the boundary layer is influscid, (i. e. , the author's generalization of the

word inviscid, to include the absence of all three molecular flux pro-

cesses: viscosity, conduction and diffusion), and here standard mathe-

matical techniques such as the relaxation method and the method of characteristics, can be applied to the determination of the gaseous state in the subsonic and supersonic portions of the hypersonic flow field.

It is noted that the bands shown in Fig. 1 represent the approximate extent of the smooth transitions from one flow regime into the adjacent regime where for the sake of illustration, the nose radius of the vehicle was taken approximately equal to 0.1 ft. An increase in vehicle nose radius has the effect of shifting all of these regimes to a higher altitude, while conversely, a very small object will find itself in a rarefied flow environment down to relatively low altitudes.

We must remark, however, that the most precise classification of flow regimes can occur only after all of the molecular interaction phenomena of interest are well characterized. Since internal relaxation effects are just now being included in the study of non-equilibrium hypersonic phenomena at high altitude, our ability to classify these effects is not yet complete.

FREE AND NEAR FREE MOLECULE FLOW

As noted, at extreme altitudes above the surface of a planet, where the mean free path of the gas is considerably larger than the characteristic dimensions of a space vehicle, the aerodynamic heat transfer depends on the direct collisions of the free stream particles with the surface. Therefore, the net energy transfer depends on a summation over the different types of particles which strike the surface and the energy accommodated during these collisions.

The number of particles of chemical species k incident upon an elemental area per unit time is obtained directly by a triple integration over the velocity distribution function which yields [21], [22]

$$n_k = \frac{N_k \bar{V}_k X_k}{2\sqrt{\pi}} \tag{1}$$

where the dimensionless group X_k has the following dependence upon the molecular speed ratio and angular orientation

$$X_k = e^{-(S_k \cos\theta)^2} + \sqrt{\pi} \, S_k \cos\theta \left[1 + \text{erf}(S_k \cos\theta) \right] . \tag{2}$$

In the above, N_k is the number density of species k in the free stream, S_k is the molecular speed ratio $V_\infty / \bar{V}_k$, and θ is the angle between the free stream velocity vector and the local normal to the surface. $\bar{V}_k$ is the

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most probable random speed of species k given by

$$\bar{V}_k = \sqrt{2gR_kT} \qquad (3)$$

For large values of the product $S_k\cos\theta$ the exponential term approaches zero, the error function approaches unity and (1) becomes simply:

$$n_k = N_k V_\infty \cos\theta \qquad (4)$$

The total energy flux incident upon the elemental area of surface per unit time in a free molecular flow, may be obtained by summation over the contribution of all of the different species:[23]

$$E_\infty = \sum_k n_k \left[\frac{m_k V_\infty{}^2}{2} + \ast T(\psi_k + \mathcal{E}_k) + m_k(\Delta h^o_{f_k} + I_k) \right]_\infty \qquad (5)$$

where

$$\psi_k = \frac{5\chi_k e^{(S_k\cos\theta)^2} - 1}{2\chi_k e^{(S_k\cos\theta)^2}} \qquad (6)$$

and m_k is the mass of a particle of the kth kind. The three terms in the square brackets are respectively, the kinetic energy, the internal energy and the chemical energy of the incident particles. The dimensionless

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quantity $\mathcal{E}_k$ includes the rotational and vibrational energies carried by diatomic and polyatomic species. The chemical energy term includes the heat of formation of the neutral atomic species $\Delta h^o_{f_k}$ and the ionization potential I_k of the charged species.

If the incident particles are reflected diffusely, the emitted gas would have no macroscopic velocity with respect to the surface and would be in maxwellian equilibrium at the surface temperature. The emitted particles would have a microscopic velocity, however, which is associated with their random motion equilibrated to the thermal energy of the surface. In this case the total energy transported away from the surface becomes

$$E_w = \frac{\rho_w}{2\pi} \left[T_w \sum_k C_k R_k \overline{V}_k (2 + \mathcal{E}_k) + \sum_k C_k \overline{V}_k (\Delta h^o_{f_k} + I_k) \right]_w \qquad (7)$$

where ρ_w is the mass density of the emitted gas at the surface, and C_k is the mass fraction of species k of the gas emitted at the surface.

In general, the reflected particles will not have their energies completely accommodated to the surface conditions and will rebound at some energy intermediate between the surface conditions and ambient conditions, that is, $E_r \neq E_w$. Therefore, the net aerodynamic heat transfer in the free molecule flow regime is not simply $E_\infty - E_w$. In order to determine the portions of the incident energies, (i.e., kinetic, internal,

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or chemical) which are transferred to the surface, detailed information

is needed concerning the interactions of the impinging particles with

the solid. The reader is referred to two recent review articles on the

subject of thermal accommodation, [24, 25] and it is merely noted here that

a whole multi-dimensional matrix of surface interactions exists. That

is, a matrix of coefficients $\alpha_{k, \varphi, s \ldots}$ can be introduced to specify the

degree to which a particular form of energy, not including chemical,

$E^1_{k, \varphi}$, carried by one type of particle, species k, is accommodated by

a surface composed of material "s",[23]

$$\alpha_{k, \varphi, s \ldots} = \left(\frac{E^1_\infty - E^1_r}{E^1_\infty - E^1_w} \right)_{k, \varphi, s \ldots} \tag{8}$$

where E^1_r is the energy which is actually transported away from the sur-

face by the reflected particles, and E^1_w is the energy which would be trans-

ported away if complete accommodation occurs. It is expected that, in

general, $\alpha_{k, \varphi, s \ldots}$ are not constant, but depend on the mode and level

of the energy carried by the kth kind of particles, as well as the condition

of the surface, including the substrate material and any adsorbed films

of contaminants.

Some theoretical estimates are available for predicting the

magnitude of α including the classical mechanical approach of Baule[26]

and the more recently developed quantum mechanical methods. [27-29]

A limited amount of experimental data are also available,[23-25] but it must be emphasized that, in general, only a very small portion of the matrix of interactions has been explored. The theories have been developed primarily for the thermal accommodation of translational energy. The experiments have usually been conducted either with monatomic gases or such low energy levels in the incident particles that the gas surface interactions do not in any way simulate hyperthermal flows. Other experiments have also been performed, but with uncharacterized surfaces, and hence these data, have little or no significance.

The portion of the incident chemical energy which may be released at a surface depends upon the ability of the surface to promote catalytic atom and ion recombination. However, published data are again quite meager.[23, 30] It is noted that a theoretical study of the variation of the catalytic efficiency γ_k with surface temperature and surface concentration has been carried out recently for atomic oxygen.[31]

From the foregoing it is clear that although general relationships have been derived[23] for the aerodynamic heat transfer in the free molecule flow regime, at least three types of uncertainties can be identified.

> 1. The fraction of the thermal energy (kinetic
>   and internal) accommodated by the surface
>   for hypersonic flow conditions is not neces-

sarily known because little data exists on the

matrix of interactions $\alpha_{k, \varphi, s}$.

2. The level of uncertainty in the composition of

the upper atmosphere of a given planet will

produce relatively significant changes in any

heat transfer prediction, especially for lower

molecular speed ratios and higher altitudes.

3. The mechanism of surface catalysis is not

yet understood to the extent of adequately pre-

dicting the recombination coefficients for

atoms and ions in a hypersonic environment

for different surface materials.

For the special case of hypersonic flight in the free molecule

flow regime, in an atmosphere consisting of identical, neutral non-reacting,

particles, and diffuse reflection at a convex cold vehicle surface, the aero-

dynamic heat transfer rate per unit surface area simplifies to the form:

$$Q_{F. M.}(\theta) = \frac{\alpha}{2} \rho_\infty V_\infty^3 \cos\theta \tag{9}$$

where θ is the angle between the stream and the local normal to the sur-

face. Here, $Q_{F. M.}$ represents the equilibration of a fraction of the total

directed kinetic energy of the incident particles.

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If α is equal to unity, then equation (9) also applies to concave surfaces. However, if α is less then unity, the use of equation (9) results in an underestimate of the heat transfer to concave surfaces. This follows because although, by definition, the particles reflected from the surface of either a convex or concave surface in a free molecule environment will not perturb the incident stream, for the concave surface there will be several interreflections of the incident particles between different portions of the surface. This results in a net increase in the heat transfer rate to the surface, since additional energy is transferred during each subsequent collision. In other words, for a concave surface, since multiple collisions can occur, the effective thermal accommodation coefficient exceeds the thermal accommodation coefficient per collision.

A study of free molecule flow has been carried out recently by Chahine for both concave cylindrical and spherical elements,[32] and the results he obtained for the heat transfer rate, indicate that for a given flight speed, a complex relationship exists between the geometry and the thermal accommodation coefficient. Upon examining his results at a flight interaction parameter $mV_\infty^2 / 2 \hbar T_w = 20$, and a thermal accommodation coefficient $\alpha = 0.1$, one can obtain a correlation formula for the total heat transfer to the surface of a concave spherical cap in the form:

$$(Q_{F.M.})_{concave} \approx Q_{F.M.} \left[1 + (\frac{\omega}{90^\circ})^{2.75} \right] \qquad (10)$$

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where ω is the included angle of the spherical cap. It is seen that when the surface is a complete concave hemi-sphere, i.e., $\omega = 90°$, then the heat transfer rate to the entire surface is just twice that to a convex hemi-sphere. For smaller values of ω, the correction is correspondingly less.

Having considered the free molecule flow regime in some detail, we may turn our attention to near free molecule flow. In the latter regime, one expects that since the reflected particles act to shield the vehicle from the incident particles, there will be a net reduction in the aerodynamic heat transfer, and that this effect will be more pronounced with decreasing Knudsen number.

Willis,[33] considered the near free molecule flow of a pseudo-hard sphere gas over a sphere and utilizing Krook's model,[34] and integral iteration, he obtained a result for the total heat transfer rate to the surface of the sphere which can be put into the form:

$$Q_{N.F.M.} = Q_{F.M.} \left[1 - \frac{M}{Kn_\infty} (0.53 + \frac{3.2}{M}) \right] \qquad (11)$$

In the above, M denotes the molecular speed ratio $V_\infty / \overline{C}_b$ where $\overline{C}_b$ is the random thermal velocity of a particle emitted at the body temperature of the sphere, and Kn_∞ is the ratio of the mean free path of the undisturbed gas to the radius of the sphere. Willis' results are in good agree-

ment with the earlier work of Baker and Charwat.[35]

Enoch has recently developed a new model for hypersonic rarefied gas flow, which consists essentially of introducing a delta function for portions of the distribution function appearing in the collision integral on the right hand side of the Boltzmann equation. Treating a hard sphere gas, he obtained for near free molecule, hyperthermal, Couette flow,[36]

$$Q_{N.F.M.} = Q_{F.M.} \left[1 - 2 \left(\frac{M}{Kn} \right) \left(\frac{\overline{C}_2}{\overline{C}_1} \right) \right] \tag{12}$$

where $M = V_{\infty}/\overline{C}_2$, $Kn = \sigma^2 \pi n_o d$, d is the spacing between the plates, the subscript 1 denotes plate 1 which moves at speed V_{∞}, the subscript 2 denotes plate 2 which is stationary, and $\overline{C}$ is the random thermal velocity of a particle. Although the geometries of the two flows discussed above are different, it is interesting to observe that the results for heat transfer in the near free molecule flow regime have the same functional form according to each of the theoretical models. The essential point is that to first order the near free molecular correction appears in the form M/Kn_{∞}.

MOLECULAR RELAXATION

In order to calculate the hypersonic aerodynamic and radiative heat transfer to a vehicle traveling through a multicomponent gas, it is essential that one be able to determine the gas composition and the population of thermodynamic states at all points in the flow.

First we note that the presence of a shock wave results in the conversion of most of the kinetic energy of the gas into excitation energy of random translation, rotation, vibration and electronic states of the molecules, and subsequently dissociation and ionization through coupled rate processes.

During low speed flight at low altitude, a knowledge of the various rate processes is usually not required since the gas very rapidly approaches a new state of thermochemical equilibrium downstream of the shock wave. In this case, it is sufficient to solve the Rankine-Hugoniot equations across the shock wave. With the advent of the new crop of high speed electronic computers, a number of new sets of solutions for the gas properties behind a hypersonic shock wave have recently appeared, which are more accurate than the earlier solutions and cover a broader range of flight speeds and environmental conditions.[37-40] A typical result based on the computations of Marrone[39] appears in Fig. 2. Here, the percent ionization in the gas produced behind a shock wave, defined arbitrarily as the sum of the mole fractions of all charged particles in the gas, is shown for a wide range of altitudes and flight speeds. The major assumption in utilizing these results would be that sufficient collisions occur

between the various particles in the gas, so that the gas is in thermo-chemical equilibrium.

At high altitudes, particularly in the low Reynolds number regime, although one has a fully developed shock wave, one should treat the flow by proceeding through the shock wave rather than by jumping across it.[20] Thus, one of the major difficulties in predicting the thermochemical state of the gas during high altitude flight, arises from the lack of a completely adequate knowledge of the mechanism and number of collisions required for the transfer of energy between external, internal and chemical states of the particles. We will, therefore, briefly discuss some aspects of the problem, and present several sources of theoretical and experimental data. First, we point out the recent appearance of several excellent summary references,[41-45] and note in passing that random translational excitation is extremely rapid at all temperatures of interest, requiring only several collisions. The ordinary viscosity coefficient of a gas is, in fact, a manifestation of the excitation of the random translational modes.

Although one is accustomed to thinking that rotational excitation in diatomic gases is rapid and that vibrational excitation is very slow, there is a good bit of evidence to show that while both of these statements are correct when the translational temperature is low, this is not neces-

sarily the case when the translational temperature is high.

In general, the phenomenon of the transfer of quanta of directed translational energy to an internal state is called relaxation. The relaxation time for a given mode is directly proportional to the number of collisions required to excite that mode, Z_s, (collision number), and inversely proportional to the transition probability of exciting that mode.

The theoretical determination of the transition probability generally requires a molecular model of intermolecular interactions and therefore of the intermolecular potential function.

Experimentally, the measurable physical quantity is usually the relaxation time, or the relaxation distance, which for a measured gas velocity can be converted readily into a relaxation time. In order to compute the transition probability, or the collision number Z_s which is generally the more useful quantity, one must again assume the applicability of a theoretical intermolecular potential function.

Without going into detail, although there are basic differences between the procedures utilized in the various theoretical approaches, qualitatively, the results are nevertheless in excellent agreement. For example, the first work to receive general acceptance is that of Landau and Teller. [46] They assumed the vibrational transition probability to be dependent upon the ratio of the duration of the collision to the period of vibration. In order to compute an average transition probability, they further assumed that the velocity distribution function was maxwellian.

After several integrations they obtained

$$Z_v \sim (\frac{3}{2\pi} T^*)^{1/2} \exp\left\{\frac{3}{2} (\frac{1}{T^*})^{1/3}\right\}$$ (13)

where $T^* = kT/\epsilon$, and it is clearly seen that as the temperature rises, the average collision number Z_v decreases, which for nitrogen does not reach a minimum until 6.73×10^5 °K.

Little additional progress was made in developing the theory until Schwartz, Slawsky and Herzfeld, [47] using a simple exponential fitted to the repulsive part of the appropriate Lenard-Jones potential determined the fraction of inelastic collisions due to this potential, and hence the collisional efficiency for vibrational equilibration.

A similar, more recent, study is due to Parker[48] in which both rotational and vibrational relaxation processes were treated. His results for the number of collisions required for vibrational equilibration likewise indicate a strong inverse dependence on the translational temperature. Interestingly enough, his results for the number of collisions required for rotational excitation indicate a moderate rise with increasing translational temperature.

The theoretical results of Herzfeld, [41] Landau and Teller, [46] and Parker[48] for the number of collisions required for rotational and vibrational excitation in nitrogen are shown in Fig. 3, in comparison with the experimental data of Huber and Kantrowitz, [49] Lukasik and Young, [50]

Partington and Shilling,[51] Gaydon and Clouston,[52] Blackman,[53] Tempest and Parbrook,[54] Zmuda,[55] Greene and Hornig[56] and Parker and Adams.[57] The recent work of O'Neal and Brokaw[58] also appears. Other recent pertinent references of interest include the theoretical study of Benson, Berend and Wu,[59] and the experiments of Wray.[60]

Although the results are not shown for oxygen or nitric oxide, they have the same trend and hence it appears that both theory and the available experimental data indicate the gradual approach of Z_v and Z_r as the translational temperature rises. Since the initial translational temperature of the gas immediately within the shock wave, prior to rotational and vibrational excitation can readily approach 15,000 to 50,000°K, depending on the flight speed, Fig. 3 indicates that one should not assume that rotational and vibrational excitation occur in series inside the shock wave, if one is interested in developing a realistic model.

We have not attempted to discuss the rate of electronic excitation, nor the possible coupling between electronic exchange and vibrational excitation,[61] since not very much has been published on these effects.

In closing, we note that dissociation is most readily accomplished by the transfer of lesser amounts of energy to those molecules in the gas mixture whose upper vibrational levels are already excited rather than, say, to those in the ground state. Clearly, the rate of repopulation of the upper vibrational states is slow, since particularly energetic collisions are required. Thus, one anticipates a coupling between vibrational rela-

xation and the dissociation process. Several studies along these lines have been carried out recently by Treanor and Marrone.[62,63]

We will also not discuss here the chemical kinetics of high temperature air, except to note that this topic is treated in the following paper by Ferri and Vaglio-Laurin.[64]

AERODYNAMIC HEAT TRANSFER

In considering aerodynamic heat transfer at hypersonic speeds in the regimes where macroscopic fluid dynamic models are appropriate, one finds that there are several viscous flow problems that are receiving attention. These include low Reynolds number effects, surface catalytic effects, foreign planetary atmospheres and ionization effects at superorbital flight speeds.

The development of the theory of low Reynolds number effects has followed a logical pattern, and experiments are being performed to validate the theoretical conclusions. The earliest studies restricted to order of magnitude analyses are summarized by Hayes and Probstein.[65] Further theoretical studies including those of references 66 to 76 and the experimental data reported in references 77 to 80 have contributed to a better understanding of heat transfer in the low density regime.

The common characteristic of all of these studies is that unlike the conventional hypersonic boundary layer treatment, in which one usually ignores pressure gradients normal to the surface, here, one must consider induced pressure effects due to the interaction between the vorticity generated by the curved detached shock wave and the vortical surface layer.

In Hoshizaki's study[66] of the effect of bluntness-induced vorticity on the boundary layer, it was concluded that the inviscid momentum equations evaluated behind the shock are equivalent to using the vorticity as a boundary condition, and consequently the complete momentum equations incorporate the vorticity boundary conditions.

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Increases in the heat transfer and skin friction were obtained when the vorticity terms were retained in the Navier-Stokes equations, as the Reynolds number was decreased. However, these terms are retained in an appropriate order of magnitude analysis in the low Reynolds number regime. Probstein and Kemp,[67] Oguchi,[68] and Ho and Probstein[69] obtained essentially similar results by appealing to the low Reynolds number nature of the flow without special recourse to vorticity, except as a modification of the pressure term. It is noted that in references 66 to 68, it was assumed that the density was constant throughout the shock layer. However, Ho and Probstein[69] included the variation of the density for a non-dissociating perfect gas, and found that as the Reynolds number decreases, the variable density model yields a larger increase in heat transfer than does a constant density model. Clearly then, the variation of density across the viscous layer should be included in a realistic analysis.

The theoretical results obtained by Ferri et. al.,[70] follow the same general trend with decreasing Reynolds number as obtained by Probstein and Kemp[67] but indicate a slightly larger heat transfer rate. Recently, Levinsky and Yoshihara[71] studied the fully merged viscous layer for a monatomic gas having variable density. Qualitatively their results seem reasonable, but it must be stressed that a monatomic gas is not necessarily a good model for dissociated air at hypersonic flight speeds.

Chung,[72] attempted to include the effects of non-equilibrium chemistry in a simplified viscous shock layer model at the forward stagnation point,

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and defined the altitude range where the non-equilibrium chemical reactions in air act to produce a significant reduction in heat transfer to non-catalytic walls.

In general, the aforementioned studies all indicate that the heat transfer rate continues to rise with decreasing Reynolds number, (for ref. 71, it at least never decreases significantly). Of course, it must be remembered that these solutions are probably not valid below a shock Reynolds number below 100. However, the work of Cheng[73] does indicate a reversal in the heat transfer rate when the shock Reynolds number is less than 100. This is shown in Fig. 4 where the product of the Stanton number and the square root of the shock Reynolds number has been plotted versus the shock Reynolds number. The definitions of these quantities are as follows:

$$C_H = \frac{Q_w}{\rho_\infty \, V_\infty \, (h_s - h_w)} \tag{14}$$

$$Re_s = \frac{\rho_\infty V_\infty R_B}{\mu_s} \tag{15}$$

The results of the study of Goldberg and Scala[74] also appear in the same figure. The latter work includes the effects of dissociation, whereas Cheng's work[73] does not. One plausible inference then would be that if

the trend given by Cheng's results is correct, but that the absolute

level is too low since his gas model may not be realistic, then one obtains

the interpolated dashed curve shown in Fig. 4 as the final result over

the full low Reynolds number regime.

It is of some interest to mention also the linearized treatment

of the initial departures from boundary layer theory, due to Lenard,[75]

and the more elegant treatment due to Van Dyke.[76] In the latter study

of second order effects, that is, first order departures from boundary

layer theory, no less than seven different effects were identified, includ-

ing longitudinal curvature, transverse curvature, slip, temperature

jump, entropy gradient, stagnation enthalpy gradient and boundary layer

displacement.

The recent data of Ferri and Zakkay[77] and Dewey[78] are still

somewhat inconclusive, since real gas effects are not really present.

However, the recent experimental data of Hacker and Wilson[79] agrees

with the predictions of Van Dyke[76] in the initial vorticity interaction regime.

These data have been correlated in the form

$$\frac{(Q_w)_{vort}}{(Q_w)_{B. L.}} = 1 + \frac{0.4 \pm 0.10}{\sqrt{Re_s}}$$ (16)

where the ratio represents the increase in aerodynamic heat transfer

above the predictions of boundary layer theory. Here, it is noted that

the data were for a cold wall, where slip and temperature jump have been neglected. Potter and Miller[80] have also obtained experimental data in the low Reynolds number regime but at such low stagnation enthalpies that dissociation is negligible, and real gas effects due to internal relaxation phenomena are also probably absent.

In reviewing the status of this problem, it appears that none of the aforementioned theoretical models incorporates the merging of the shock structure with the surface viscous layer for a relaxing, dissociating gas which would be the most realistic representation of the low density non-equilibrium phenomena which are actually present in the gas at hypersonic speeds. In a similar vein, it appears that the definitive experimental data are also yet to be observed.

With regard to the influence of real surfaces in promoting chemical recombination of the dissociated species which are present in non-equilibrium air, with the attendant release of the heat of formation, the earliest studies at hypersonic speeds were carried out by Scala[81] and Goulard.[82] Since that time, additional studies have appeared sporadically. One of the most recent is that of Chung, Liu and Mirels,[83] who investigated the effect of a stepwise discontinuity in the catalytic efficiency on the heat transfer to the surface.

With the coming to fruition of the nation's plan for space exploration, a problem of increasing technological significance is that of the

influence of the chemical composition of the gas upon the heat transfer

rate. That is, before space probes can actually enter the atmospheres

of the near planets to actually determine their structure and chemical

composition, a means must be found to design the probes to withstand

the heat barrier encountered during entry, on the basis of a "reasonable"

model for the undisturbed environment, e.g., Ref. 8.

Hoshizaki,[89] has investigated the laminar heat transfer in carbon

dioxide including the effects of dissociation. Scala and Gilbert[85]

carried out a study of the laminar heat transfer in eight different disso-

ciating gas mixtures covering a range of molecular weight from two (pure

hydrogen) to forty-four (pure carbon dioxide). All of their numerical

solutions to a high order set of coupled non-linear differential equations

with variable coefficients (hypersonic boundary layer with variable trans-

port and thermodynamic properties) are shown in Fig. 5. These results

were then correlated in terms of a simple formula for stagnation point

heat transfer, which represents all the data to within ± 8%.[85]

$$Q_w \sqrt{\frac{R_B}{P_{stag}}} = (12 + 0.866\overline{M}_\infty) \times 10^{-3}(h_e - h_w) \frac{BTU}{Ft.^{3/2}sec.\ atm.^{1/2}} \qquad (17)$$

where the symbols have the following meaning and physical dimensions:

Q_w - heat transfer rate $\dfrac{BTU}{ft.^2\ sec.}$

h_e - stagnation enthalpy, BTU/lb.

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h_w - enthalpy of gas at surface, BTU/lb.

R_B - vehicle nose radius, ft.

P_e - stagnation pressure, atm.

$\overline{M}_\infty$ - molecular weight of gas upstream of shockwave

The agreement between the available experimental data[86-88] and this correlation formula is good.

An area of current controversy is that of the effect of ionization in the gas upon hypersonic heat transfer. The results of the various protagonists appears summarized in Fig. 6.

The early work of Rutowski[89] does not appear since it was carried out for argon. The theories of Adams,[90] Cohen[91] and Hoshizaki[84] are seen to be essentially in agreement with each other. Their results indicate that the effects of ionization in air do not produce a marked increase in the heat transfer rate above that which would have been calculated utilizing a dissociated gas correlation (extrapolation). Scala[92, 93] utilized a different set of transport properties and treated the diffusion process by means of a four component gas model, consisting of molecules, atoms, ions and electrons. His results indicate a marked increase in heat transfer rate due to the presence of ions and electrons.

At the low flight speed end, all of the theories are in agreement with the data of Rose and Stark.[94] However, at the high flight speed end of the scale, the experimental data of Warren et. al.,[93, 95] supports the gas model utilized in the theory of Scala, whereas the data of Offenhartz et. al.,[96]

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and Hoshizaki,[84] supports the other theories. From a theoretical viewpoint this question can be resolved when better data are available for the collision cross sections of the interacting species at high temperature and the best model for the diffusion process is established. From the experimental view, it would be good to establish that a given experimental facility has adequate test time, and that spurious effects due to gas radiation are not being introduced.

RADIATIVE HEAT TRANSFER

The problems associated with the determination of the radiative energy transfer from the hot gas cap (shock layer) to an entry vehicle are formidable, and different quantum mechanical techniques have been developed in order to predict the contributions to the radiative flux. [97-104]

Lambert's Law for the absorption of radiant energy may be written:

$$I = I_0 e^{-\chi x} = I_0 e^{-N\sigma x} \tag{18}$$

where I_0 is the intensity of the incident beam, I is the intensity in the beam after it traverses x units of the gas, χ is the linear absorption coefficient of the gas, σ is the cross section for this absorption and N is the density of absorbing particles. This equation applies:

1. at a particular radiant frequency

2. as a mean over a band of frequencies

3. as a mean over the entire spectrum.

It should be noted that N and σ must be individually considered for each of the types of radiation absorbing processes, and, if there are several for the frequency region of interest, they must be summed.

If it is assumed that local thermodynamic equilibrium prevails,

or equivalently that Kirchoff's Law holds, then the gaseous emissivity may be written:

$$\epsilon = 1 - e^{-\chi x} \quad .$$

(19)

Then, also the emissivity expressions introduced in Eqs. 18 and 19 may be used to obtain the actual radiant intensity:

$$I_\nu = \epsilon_\nu B_\nu = B_\nu (1 - e^{-\sigma N x})$$

(20)

where B_ν, the Planck black body curve, is given by:

$$B_\nu = \frac{8\pi h \nu^3}{c^3} \left[\exp\left(\frac{h\nu}{kT}\right) - 1 \right]^{-1} \quad .$$

(21)

Here, B_ν refers to a given frequency ν, but if we desire the result over the entire spectrum, we may write:

$$I = \bar{\epsilon} \, \bar{\sigma} \, T^4; \qquad \bar{\sigma} = \frac{2k^4 \pi^5}{15 h^3 c^2}$$

(22)

and, of course, the total black body intensity may be re-expressed in any desired units.

The general problem consists of obtaining the cross section or

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absorption coefficient for whatever processes contribute to the radiation form a high temperature partially ionized CON gaseous system. Since the air system has already been treated extensively, we will first briefly list those processes which have already been found to be important for radiation from air at temperatures corresponding to sub-orbital flight speeds, and then we will add the additional processes which occur at supercircular flight speeds or which are due to chemical species containing carbon. In the temperature range of interest, one has

a. Ultraviolet-visible Band Spectra

The beta system of NO

The gamma system of NO

The Schuman-Runge system of oxygen

The first positive system of nitrogen

The second positive system of nitrogen

The first negative system of the positive nitrogen ion

b. Infrared Band Spectra

The infrared spectrum of NO

c. Bound Free Continua

The bound free continuum of the negative oxygen ion

d. Free Free Continua

The free free continuum of oxygen

The free free continuum of nitrogen

To this list, it is postulated that for a CON gaseous mixture, at elevated temperature, one must add[104]

a. Ultraviolet-visible Band Spectra

The CO_2 system

The CN system

The CO band system

The C_2 band system

b. Infrared Band Spectra

The infrared spectrum of CO_2

The infrared spectrum of CN

The infrared spectrum of CO

c. Bound Free Continua

The bound free continuum of atomic carbon

The bound free continuum of negative carbon ions

d. Free Free Continua

The free free continuum of the positive oxygen ion

The free free continuum of the positive nitrogen ion

The free free continuum of atomic carbon

e. Deionization Continua

The deionization continuum of oxygen

The deionization continuum of nitrogen

Two points must be made here. The first is that one does not

necessarily know in advance of the actual computations which bands will yield significant contributions in a given frequency range. The second is that the calculated values of the radiant energy transfer coefficients depend on the concentrations of the species, and hence the contributions of chemical species containing only oxygen and/or nitrogen given in the first list would not contribute in the same manner in a CON system as in an air system.

We will not go into the details of the various computation procedures, but will merely present a typical set of results for the radiative heat transfer rate Q_R, obtained by Breene and Nardone.[100] In Fig. 7, we have shown the dependence of Q_R upon the gas temperature and density for equilibrium air 1 cm. in thickness. These values may be scaled up or down directly as the thickness of the shock layer. Of course, for a thick gas layer, the numerical value of Q_R should never exceed the black body limit, since $\epsilon \leq 1.0$. Here, again, it appears that there is some controversy since these results differ from those published by other investigators by as much as a factor of three to ten. It is noted that this is not simply due to a choice of "f" numbers, rather it is due to the fact that Breene has considered a distribution of oscillator strengths rather than simply summing over bands.

Some remarks must be made concerning "non-equilibrium" radiation. First, we distinguish between non-equilibrium radiation due to the

absence of thermal equilibrium, in which case there is a temperature overshoot due to the relaxation phenomena associated with equipartition of energy in a mixture of diatomic gases. An indication of the temperature overshoot can be obtained from the recent work of Scala and Talbot[20] on shock wave structure. The other type of non-equilibrium radiation, which arises as a consequence of the absence of chemical equilibrium in the gas is more readily evaluated by considering the chemical kinetics of the flow. [105, 106]

Finally, in closing it is noted that at hypervelocity flight speeds, the aerodynamic and radiative heating can be of comparable magnitude and the possibility of coupling between them should be considered. Some recent studies along this line appear in Refs. 107-109, and a definitive treatment of the equations governing the coupling between radiation and the macroscopic equations of motion is to appear shortly. [110]

CONCLUSIONS

There have been many significant advances in the development of techniques for the prediction of the aerodynamic and radiative heat transfer in multicomponent gases at hypersonic speeds. In particular, one may state that the field of aerothermochemistry has tended to keep pace with the burgeoning needs of aerospace technology. That is, aerodynamicists and mathematicians by working in collaboration with physical chemists have successfully learned how to incorporate the concepts of thermochemistry and chemical kinetics into models for high temperature multicomponent fluid flow.

Furthermore, certain fundamental aspects of thermophysical phenomena are also receiving increased attention. In particular, statistical mechanical (kinetic theory) and quantum mechanical approaches are being employed in the development of microscopic models for the interaction processes that occur in high temperature gas streams.

However, much work remains to be done, and hence we can look forward to an increased collaboration between aerodynamicists, physicists, mathematicians and physical chemists in the future.

ACKNOWLEDGMENTS

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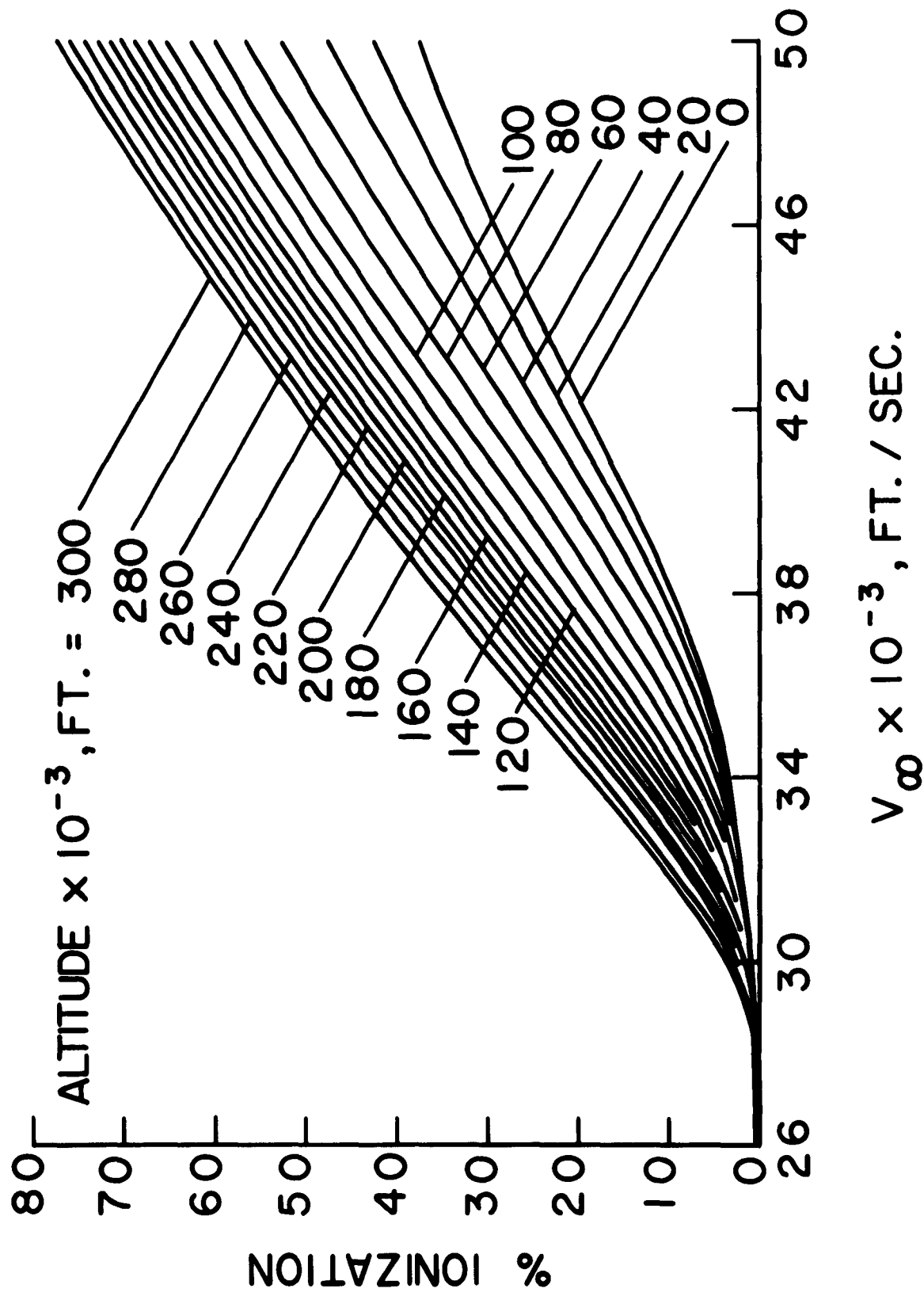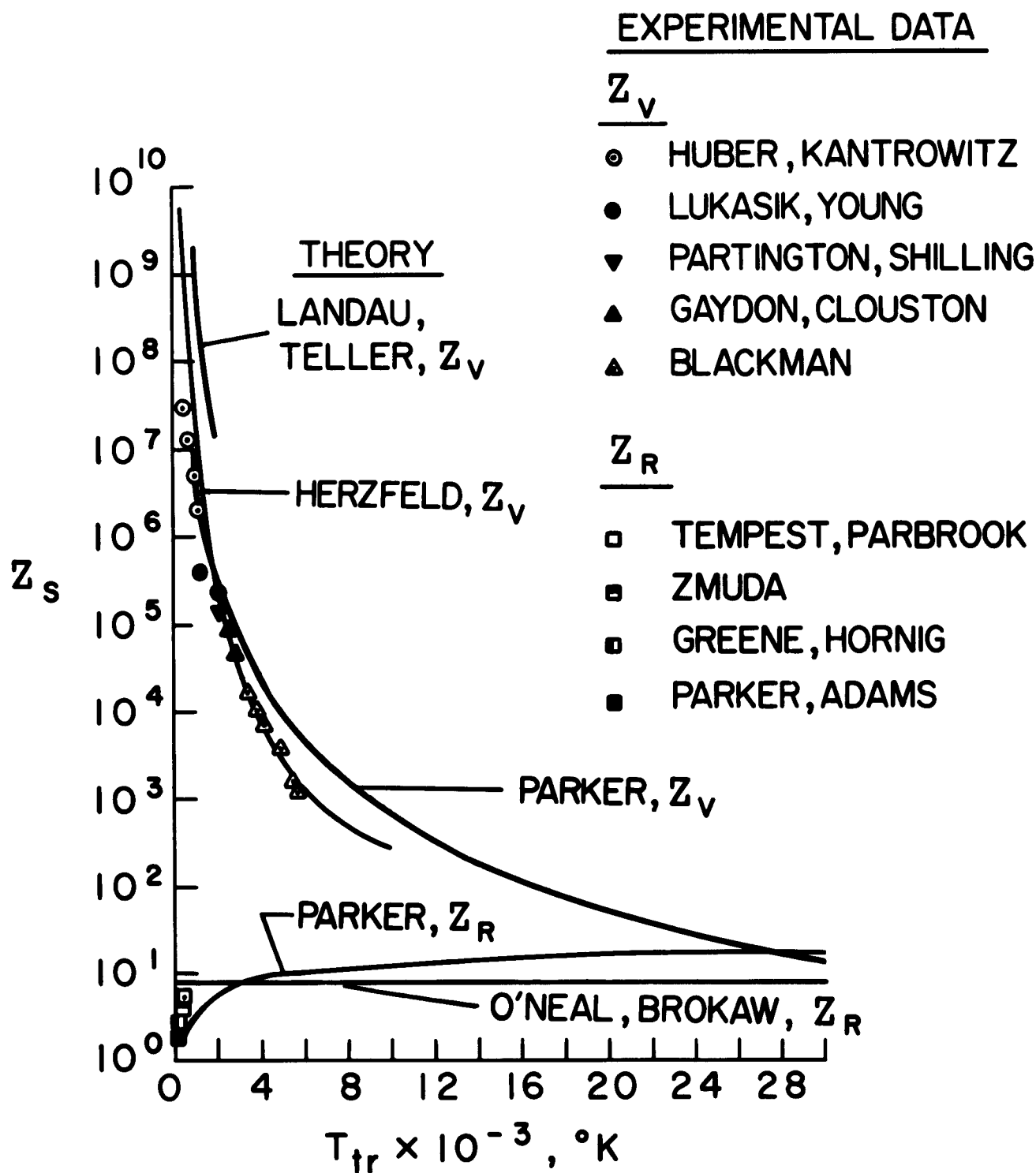
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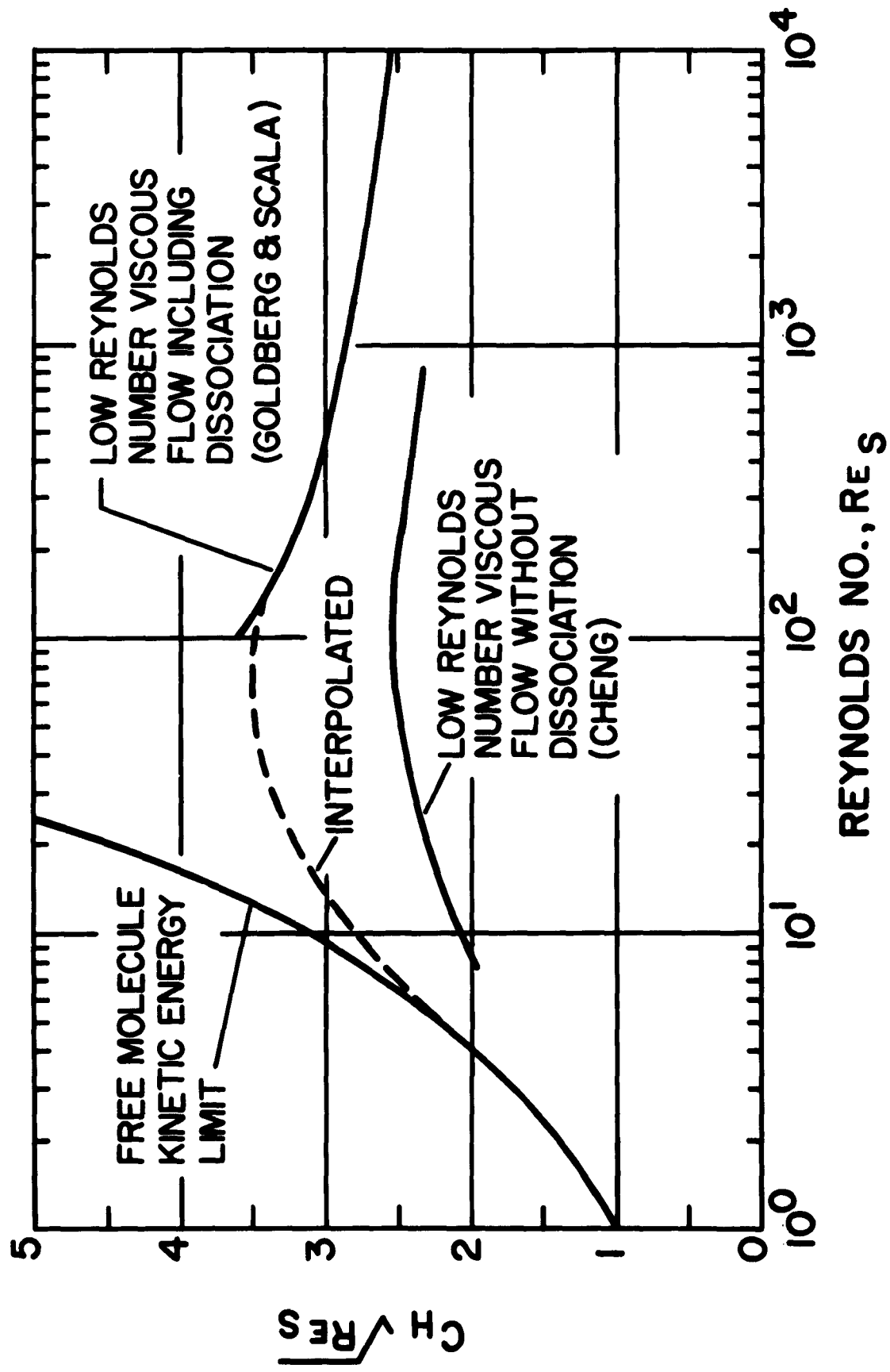OF ROTATIONAL AND VIBRATIONAL MODES IN NITROGEN

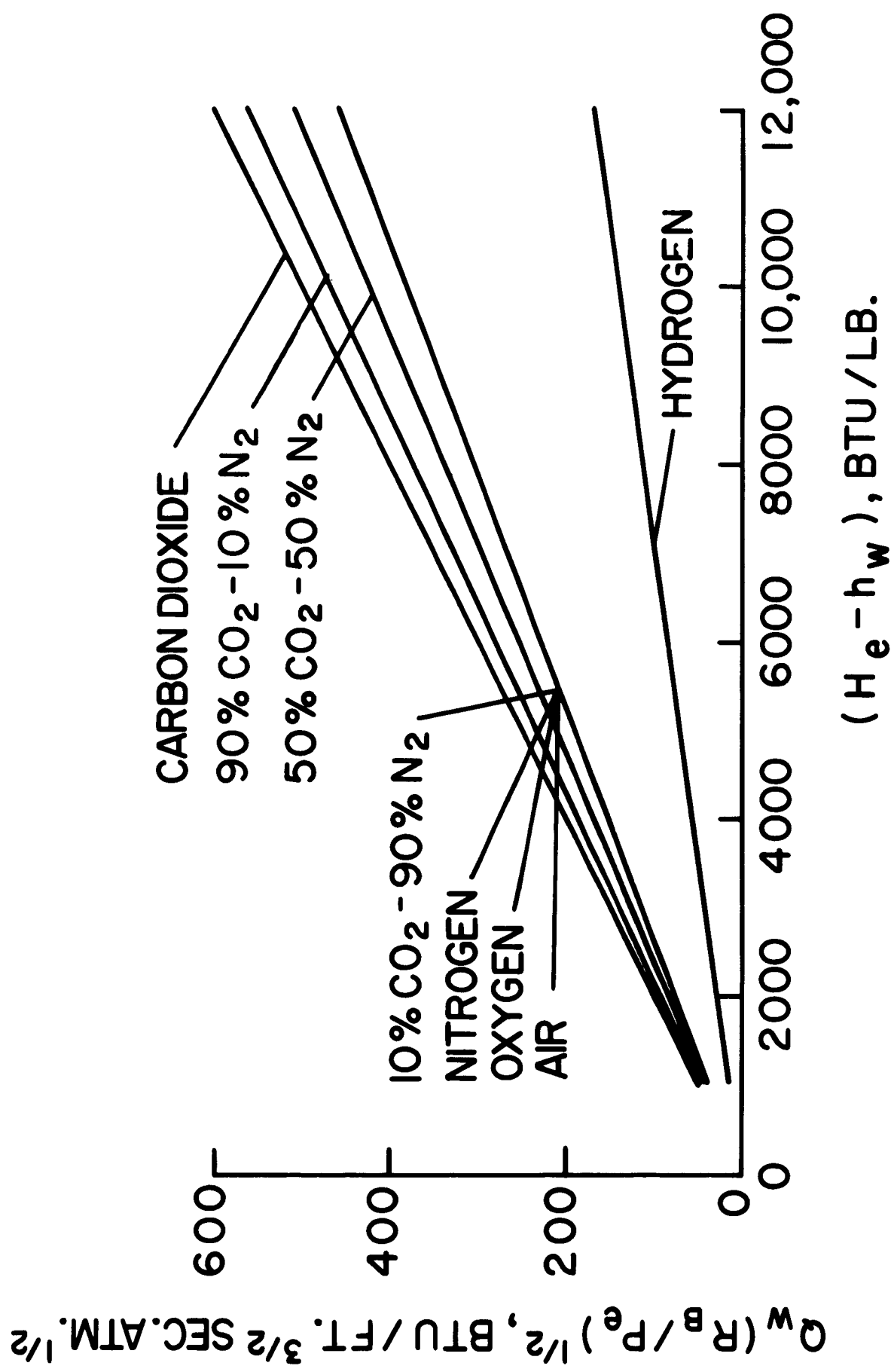FIGURE 4. STANTON NUMBER VS. REYNOLDS NUMBER

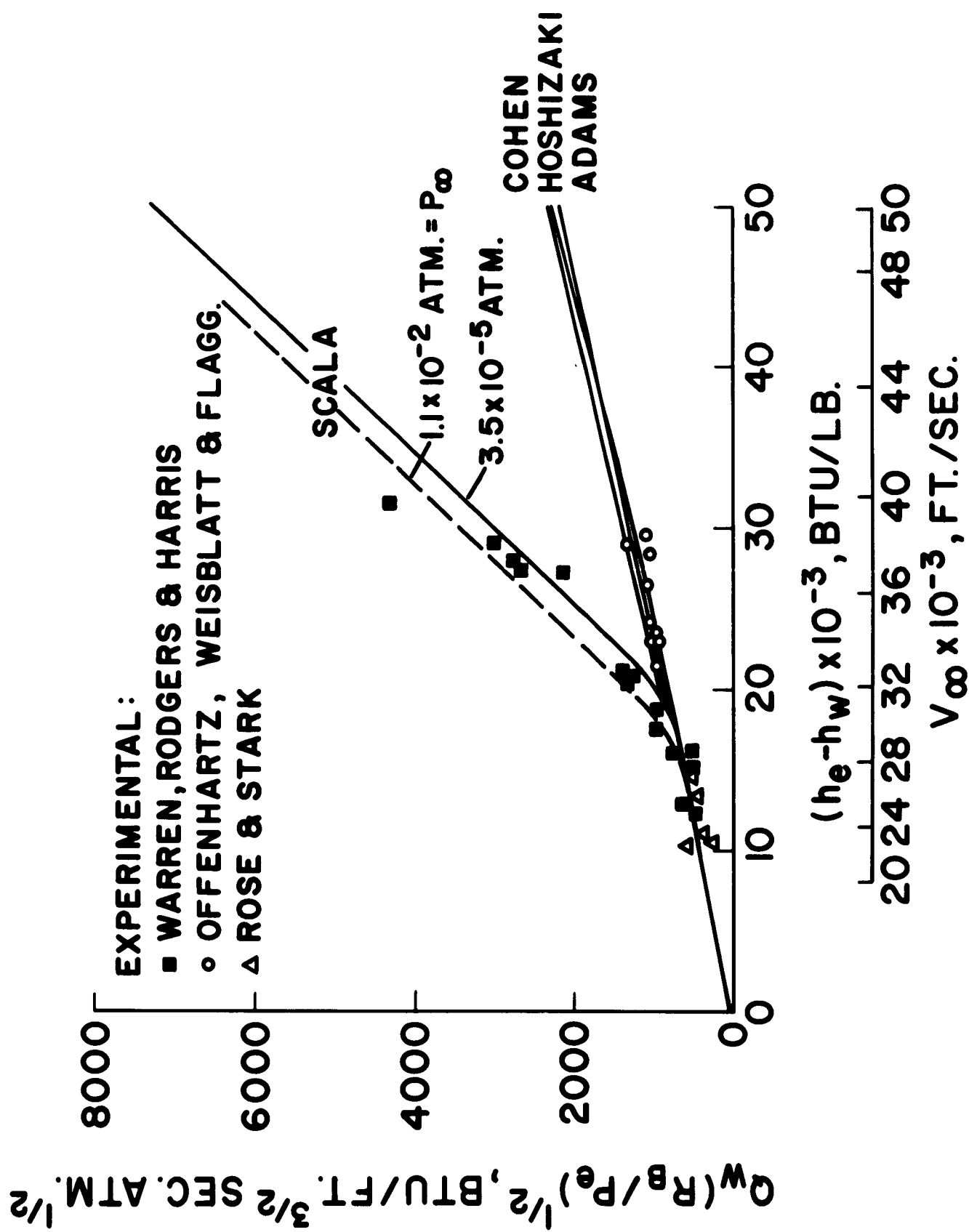FIGURE 5.   VARIATION OF CORRELATED HEATING RATES WITH ENTHALPY DIFFERENCE

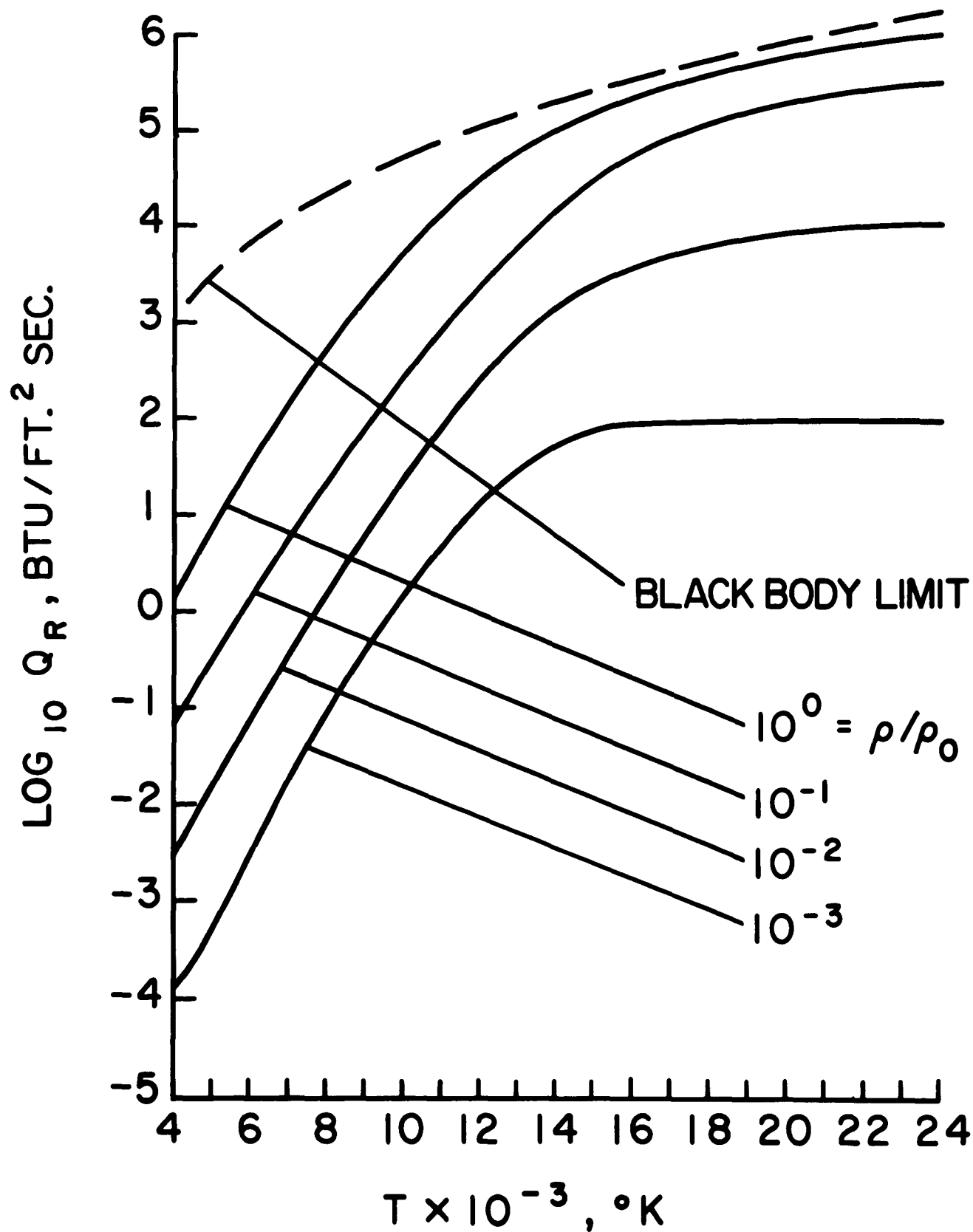FIGURE 6. HYPERVELOCITY STAGNATION POINT HEAT TRANSFER

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TECHNICAL INFORMATION SERIES
Title Page

AUTHOR	SUBJECT CLASSIFICATION	NO. R62SD987
S. M. Scala	Hypersonic Aerodynamics, Heat Transfer	DATE December 1962

TITLE THE HYPERSONIC ENVIRONMENT --
HEAT TRANSFER IN MULTICOMPONENT GASES

ABSTRACT   Some of the latest techniques for predicting aerodynamic and radiative heat transfer are discussed and uncertainties are pointed out. Throughout the paper, special emphasis has been placed on a discussion of thermophysical phenomena, which points out the need for the introduction of classical, statistical and quantum mechanical approaches to the development of realistic models for the hypersonic interaction problem.

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CONCLUSIONS

There have been many significant advances in the development of techniques for the prediction of the aerodynamic and radiative heat transfer in multicomponent gases at hypersonic speeds. In particular, one may state that the field of aerothermochemistry has tended to keep pace with the burgeoning needs of aerospace technology.

However, much work remains to be done, and hence we can look forward to an increased collaboration between aerodynamicists, physicists, mathematicians and physical chemists in the future.

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For list of contents—drawings, photos, etc. and for distribution see next page (FN-610-2).

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